
Divining gold in seafloor polymetallic massive sulfide systems
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Electronic supplementary material 1

References for the geochemical data presented in this paper and ESM 2:

Akinfiyev NN, Tagirov BR (2014) Zn in hydrothermal systems: Thermodynamic description of hydroxide, chloride, and hydrosulfide complexes. *Geochem Int* 52:197–214.

Akinfiyev NN, Zotov AV (2001) Thermodynamic description of chloride, hydrosulfide, and hydroxo complexes of Ag (I), Cu (I), and Au (I) at temperatures of 25–500°C and pressures of 1–2000 bar. *Geochem Int* 39:990-1006.

Akinfiyev NN, Zotov AV (2010) Thermodynamic description of aqueous species in the system Cu-Ag-Au-S-O-H at temperatures of 0–600°C and pressures of 1–3000 bar. *Geochem Int* 48:714–720.

Bel'tenev V, Shagin A, Markov V, Rozhdestvenskaya I, Stepanova T, Cherkashev G, Fedorov I, Rumyantsev A, Poroshina I (2004) A new hydrothermal field at 16°38.4'N, 46°28.5'W on the Mid-Atlantic Ridge. *InterRidge News* 13:5–6.

Binns RA (2006) Data Report: Geochemistry of massive and semimassive sulfides from Site 1189, Ocean Drilling Program Leg 193, In: Barriga FJAS, Binns RA, Miller DJ, Herzig PM (eds.) *Proceedings of the Ocean Drilling Program Scientific Results Leg 193*. Texas A&M University, College Station, pp. 1–22.

Binns RA (2014) Bikpela: A Large Siliceous Chimney from the PACMANUS Hydrothermal Field, Manus Basin, Papua New Guinea. *Econ Geol* 109:2243-2259.

Bogdanov YA, Lein AY, Maslennikov VV, Li S, Ulyanov AA (2008)

Mineralogical- geochemical features of sulfide ores from the Broken Spur hydrothermal vent field. *Oceanology* 48:679–700.

Bogdanov YA, Lein AY, Sagalevich AM (2005) Chemical Composition of the

Hydrothermal Deposits of the Menez Gwen Vent Field (Mid-Atlantic Ridge). *Oceanology* 45:849–856.

Bogdanov YA, Lein AY, Sagalevich AM, Ulyanov AA, Dorofeev SA, Ulyanova NY

(2006a) Hydrothermal sulfide deposits of the Lucky Strike vent field, Mid-Atlantic Ridge. *Geochem Int* 44:403–418.

Bogdanov YA, Lein AY, Ulyanov AA, Maslennikov VV, Ulyanova NY, Sagalevich AM

(2006b) Initial stage of the hydrothermal ore accumulation within the field at 9°50' N on the East Pacific Rise. *Oceanology* 46:81–94.

Bruland KW, Lohan MC (2004) 6.02 Controls of Trace Metals in Seawater. In: Holland HD,

Turekian KK (eds) *Treatise on geochemistry*. Elsevier/Pergamon, Amsterdam - Boston, pp 23-47.

Campbell AC, Edmond JM, Colodner D, Palmer MR (1987) Chemistry of hydrothermal fluids

from the Mariana Trough back arc basin in comparison to mid-ocean ridge fluids. *EOS Tran Am Geophys Union* 68:1531.

Charlou JL, Donval JP, Fouquet Y, Jean-Baptiste P, Holm N (2002) Geochemistry of high H₂

and CH₄ vent fluids issuing from ultramafic rocks at the Rainbow hydrothermal field (36°14'N, MAR). *Chem Geol* 191:345–359.

Craddock PR (2009) Geochemical tracers of processes affecting the formation of seafloor

hydrothermal fluids and deposits in the Manus back-arc basin. Dissertation, Massachusetts Institute of Technology and Woods Hole Oceanographic Institution, Woods Hole.

Cruz MIFS (2015) Mineralogy and geochemistry of contrasting hydrothermal systems on the

Arctic Mid Ocean Ridge (AMOR): The Jan Mayen and Loki's Castle vent fields.

Dissertation, Universidade de Lisboa, pp. 257.

de Ronde CE, Hannington MD, Stoffers P, Wright IC, Ditchburn RG, Reyes AG, Baker ET,

Massoth GJ, Lupton JE, Walker SL, Greene RR, Soong CWR, Ishibashi J, Lebon G

(2005) Evolution of a submarine magmatic-hydrothermal system: Brothers volcano,

southern Kermadec arc, New Zealand. *Econ Geol* 100:1097–1133.

de Ronde CEJ, Massoth GJ, Butterfield DA, Christenson BW, Ishibashi J, Ditchburn RG,

Hannington MS, Brathwaite RL, Lupton JE, Kamenetsky VS, Graham IJ, Zellmer GF,

Dziak RP, Embly RW, Dekov VM, Munnik F, Lahr J, Evans LJ, Takai K (2011)

Submarine hydrothermal activity and gold-rich mineralization at Brothers Volcano,

Kermadec Arc, New Zealand. *Miner Deposita* 46:541–584.

de Ronde CEJ, Walker SL, Ditchburn RG, Caratori Tontini F, Hannington MD, Merle SG,

Timm C, Handler MR, Wysoczanski RJ, Dekov VM, Kamenov GD, Baker ET, Embley

RW, Lupton JE, Stoffers P (2014). The anatomy of a buried submarine hydrothermal

system, Clark volcano, Kermadec arc, New Zealand. *Econ Geol* 109:2261–2292.

Douville E, Charlou JL, Oelkers E, Biennu, P, Jove-Colon CF, Donval JP, Fouquet Y, Prieur

D, Appriou P (2002) The rainbow vent fluids (36°14'N, MAR): the influence of ultramafic

rocks and phase separation on trace metal content in Mid-Atlantic Ridge hydrothermal

fluids. *Chem Geol* 184:37–48.

Evans GN, Tivey MK, Seewald JS, Wheat CG (2017). Influences of the Tonga Subduction

Zone on seafloor massive sulfide deposits along the Eastern Lau Spreading Center and

Valu Fa Ridge. *Geochim Cosmochim Acta* 215:214–246.

Falkner KK, Edmond JM (1990) Gold in seawater. *Earth Planet Sc Lett* 98:208–221.

- German CR, Damm Von KL (2004) 6.07 - Hydrothermal Processes. In: Holland HD, Turekian KK (eds) Treatise on geochemistry. Elsevier/Pergamon, Amsterdam - Boston, pp 181–222.
- Glasby GP, Iizasa K, Hannington M, Kubota H, Notsu K (2008) Mineralogy and composition of Kuroko deposits from northeastern Honshu and their possible modern analogues from the Izu-Ogasawara (Bonin) Arc south of Japan: Implications for mode of formation. *Ore Geol Rev* 34:547–560.
- Hall G, Vaive J, Hannington MD, McConachy TF (1988) Gold and associated trace elements in vent waters and suspended particulates from Southern Explorer Ridge. *EOS Tran Am Geophys Union* 69:1501.
- Hannington MD, Herzig PM, Scott S, Thompson G, Rona P (1991) Comparative mineralogy and geochemistry of gold-bearing sulfide deposits on the mid-ocean ridges. *Mar Geol* 101:217–248.
- Hannington MD, Jamieson J, Monecke T, Petersen S (2010) Modern sea-floor massive sulfides and base metal resources: toward an estimate of global sea-floor massive sulfide potential. *Rev Econ Geol Spec Publ* 15:317–337.
- Hannington MD, Petersen S, Herzig PM, Jonasson IR (2004) A global database of seafloor hydrothermal systems, including a digital database of geochemical analyses of seafloor polymetallic sulfides. Geological Survey of Canada, Open File 4598, 1 CD-ROM.
- Hannington MD, Scott SD (1989) Gold mineralization in volcanogenic massive sulfides: Implications of data from active hydrothermal vents on the modern seafloor. *Econ Geol Monogr* 6:491–507.
- Hansen J (2013) Sulfide petrology and element geochemistry of a black smoker from the inactive Sonne hydrothermal site, Indian Ocean. Master Thesis, Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen, pp. 83.

- Hein JR, de Ronde CEJ, Koski RA, Ditchburn RG, Mizell K, Tamura Y, Stern RJ, Conrad TA, Ishizuka O, Leybourne MI (2014) Layered hydrothermal barite-sulfide mound field, East Diamante caldera, Mariana volcanic arc. *Econ Geol* 109:2179–2206.
- Hocking MWA (2007) The Calypso Hydrothermal Vent Field: The Seafloor Expression of an Active Submarine Low-Sulphidation Epithermal System, Bay of Plenty, New Zealand. Master Theses, University of Ottawa, pp. 177.
- Ikehata K, Suzuki R, Shimada K, Ishibashi J-I, Urabem T (2015) Mineralogical and Geochemical Characteristics of Hydrothermal Minerals Collected from Hydrothermal Vent Fields in the Southern Mariana Spreading Center. In: Ishibashi J-I, Okino K, Sunamura M (eds) *Subseafloor Biosphere Linked to Hydrothermal Systems*. Springer Japan, Tokyo, pp 275–287.
- Iizasa K, Asada A, Mizuno K, Katase F, Lee S, Kojima M, Ogawa N (2019) Native gold and gold-rich sulfide deposits in a submarine basaltic caldera, Higashi-Aogashima hydrothermal field, Izu-Ogasawara frontal arc, Japan. *Miner Deposita* 54:117–132.
- Kakegawa T, Utsumi M, Marumo K (2008) Geochemistry of Sulfide Chimneys and Basement Pillow Lavas at the Southern Mariana Trough (12.55°N-12.58°N). *Resour Geol* 58:249–266.
- Kilias SP, Nomikou P, Papanikolaou D, Polymenakou PN, Godelitsas A, Ariadne A, Steven C, Gamaletsos P, Mertzimekis TJ, Stathopoulou E, Goettlicher J, Steininger R, Betzelou K, Livanos I, Isidoros I, Christakis C, Bell KC, Scoullou M (2013) New insights into hydrothermal vent processes in the unique shallow-submarine arc-volcano, Kolumbo (Santorini), Greece. *Sci Rep* 3:2421.
- Kim J, Lee I, Halbach P, Lee KY, Ko, YT, Kim KH (2006) Formation of hydrothermal vents in the North Fiji Basin: Sulfur and lead isotope constraints. *Chem Geol* 233:257–275.

- Kim J, Lee KY, Kim JH (2011) Metal-bearing molten sulfur collected from a submarine volcano: Implications for vapor transport of metals in seafloor hydrothermal systems. *Geology* 39:351–354.
- Kristall B, Nielsen D, Hannington MD, Kelley DS, Delaney JR (2011) Chemical microenvironments within sulfide structures from the Mothra Hydrothermal Field: Evidence from high-resolution zoning of trace elements. *Chem Geol* 290:12–30.
- Kuznetsov V, Tabuns E, Kuksa K, Cherkashov G, Maksimov F, Bel'Tenev V, Lazareva L, Zhrebtsov I, Grigoriev V, Baranova N (2015) The oldest seafloor massive sulfide deposits at the Mid-Atlantic Ridge: $^{230}\text{Th}/\text{U}$ chronology and composition. *Geochronometria*.
- Li Y-H (1991) Distribution patterns of the elements in the ocean: A synthesis. *Geochim Cosmochim Acta* 55:3223–3240.
- Liao S, Tao C, Li H, Barriga FJAS, Liang J, Yang W, Yu J, Zhu C (2018) Bulk geochemistry, sulfur isotope characteristics of the Yuhuang-1 hydrothermal field on the ultraslow-spreading Southwest Indian Ridge. *Ore Geol Rev* 96:13–27.
- Marques AFA, Barriga FJAS, Scott SD (2007) Sulfide mineralization in an ultramafic-rock hosted seafloor hydrothermal system: From serpentinization to the formation of Cu–Zn–(Co)-rich massive sulfides. *Mar Geol* 245:20–39.
- Mozgova, NN, Krasnov SG, Borodaev YS, Stepanova TV, Cherkashev GA, Lalou C, Samovarov MS (1998). The structure, mineral associations, and noble metals of the Mir oceanic ore mound, the TAG Hydrothermal Field (Mid-Atlantic Ridge, 26°N Latitude). *Geol Ore Deposit* 40:228–249.
- Nautilus Minerals Inc. (2006a) Press Release. May 25, 2006.
- Nautilus Minerals Inc. (2006b) Press Release. September 05, 2006.

- Nautilus Minerals Inc. (2006c) Press Release. September 26, 2006.
- Nautilus Minerals Inc. (2007a) Press Release. June 22, 2007.
- Nautilus Minerals Inc. (2007b) Press Release. November 13, 2007.
- Nautilus Minerals Inc. (2008) Press Release. December 12, 2008.
- Nautilus Minerals Inc. (2009) News Release. June 11, 2009.
- Nautilus Minerals Inc. (2012) Press Release. November 1, 2012.
- Noguchi T, Oomori T, Tanahara A, Taira N, Takada J, Taira H (2007) Chemical composition of hydrothermal ores from Mid-Okinawa Trough and Suiyo Seamount determined by neutron activation analysis. *Geochem J* 41:141–148.
- Noguchi T, Shinjo R, Ito M, Takada J, Oomori T (2011) Barite geochemistry from hydrothermal chimneys of the Okinawa Trough: insight into chimney formation and fluid/sediment interaction. *J Miner Petrol Sci* 106:26–35.
- Nozaki T, Ishibashi J-I, Shimada K, Nagase T, Takaya Y, Kato Y, Kawagucci S, Watsuji T, Shibuya T, Yamada R, Saruhashi T, Kyo M, Takai K (2016) Rapid growth of mineral deposits at artificial seafloor hydrothermal vents. *Sci Rep* 6:22163–23.
- Paduan JB, Zierenberg RA, Clague DA, Spelz RM, Caress DW, Troni G, Thomas H, Glessner J, Lilley MD, Lorenson T, Lupton J, Neumann F, Santa Rosa-del Río MA, Wheat CG (2018). Discovery of hydrothermal vent fields on Alarcón Rise and in southern Pescadero Basin, Gulf of California. *Geochem Geophys Geosy* 19:4788–4819.
- Perfetti E, Pokrovski GS, Ballerat-Busserolles K, Majer V, Gibert F (2008) Densities and heat capacities of aqueous arsenious and arsenic acid solutions to 350°C and 300bar, and revised thermodynamic properties of , and iron sulfarsenide minerals. *Geochim Cosmochim Ac* 72:713–731.

Petersen S, Herzig PM, Schwarz-Schampera U, et al (2004) Hydrothermal precipitates associated with bimodal volcanism in the Central Bransfield Strait, Antarctica. *Miner Deposita* 39:358–379. doi: 10.1007/s00126-004-0414-3

Petersen S, Monecke T, Westhues A, Hannington MD, Gemmel JB, Sharpe R, Peters M, Strauss H, Lackschewitz K, Augustin N, Gibson H, Kleeberg R (2014) Drilling Shallow-Water Massive Sulfides at the Palinuro Volcanic Complex, Aeolian Island Arc, Italy. *Econ Geol* 109:2129–2158.

Pokrovski GS, Akinfiev NN, Borisova AY, Zotov AV, Kouzmanov K (2014) Gold speciation and transport in geological fluids: insights from experiments and physical-chemical modelling. *Geol Soc Spec Publ* 402:9–70.

Reeves EP, Seewald JS, Saccocia P, Bach W, Craddock PR, Shanks WC, Sylva SP, Walsh E, Pichler T, Rosner M (2011) Geochemistry of hydrothermal fluids from the PACMANUS, Northeast Pual and Vienna Woods hydrothermal fields, Manus Basin, Papua New Guinea. *Geochim Cosmochim Acta* 75:1088–1123.

Seal RR, Essene EJ, Kelly WC (1990) Tetrahedrite and tennantite: evaluation of thermodynamic data and phase equilibria. *Can Mineral* 28:725-738.

SRK Consulting (2006) Independent Technical Assessment of Sea Floor Massive Sulphide Exploration Tenements in Papua New Guinea, Fiji and Tonga (No. NAT002). Nautilus Minerals Inc.

SRK Consulting (2008a) Independent technical assessment of sea floor massive sulphide exploration tenements in Papua New Guinea, Fiji, Tonga, Solomon Islands and New Zealand (No. NAT003). Report for Nautilus Minerals Inc.

SRK Consulting (2008b) 2008 Exploration Program Papua New Guinea, Tonga, Fiji, Solomon Islands and New Zealand (No. NAT004). Report for Nautilus Minerals Inc.

SRK Consulting (2010) NI43-101 Technical Report 2009 PNG, Tonga, Fiji, Solomon Islands

- and New Zealand (No. NAT006). Report for Nautilus Minerals Inc.
- SRK Consulting (2011). NI43-101 Technical Report 2010 PNG, Tonga, Fiji, Solomon Islands, New Zealand, Vanuatu and the ISA (No. NAT007). Report for Nautilus Minerals Inc.
- SRK Consulting (2012) NI43-101 Technical Report 2011: PNG, Tonga, Fiji, Solomon Islands, New Zealand, Vanuatu and the ISA (No. NAT008). Report for Nautilus Minerals Inc.
- Tao C, Li H, Huang W, Han X, Wu G-H, Su, X, Zhou N, Lin J, He Y-H, Zhou J-P (2011) Mineralogical and geochemical features of sulfide chimneys from the 49°39'E hydrothermal field on the Southwest Indian Ridge and their geological inferences. Chinese Sci Bull 56:2828–2838.
- Ueno H, Iwaida C, Yamashita I, Katakaze A (2005) Gold rich chimneys from the Mariana back-arc basin, in: Zhao C, Guo B (eds) Proceedings of the 8th Biennial SGA Meeting, Beijing (China), pp. 23-26.
- Tao C, Li H, Jin X, Zhou J, Wu T, He Y, Deng X, Gu C, Zhang G, Liu W (2014) Seafloor hydrothermal activity and polymetallic sulfide exploration on the southwest Indian ridge. Chinese Sci Bull 59:2266–2276.
- TUIM05MV Database (2005) Geochemistry data from Sulfide samples from the Lau Back-arc Basin acquired during Melville expedition TUIM05MV. MGDS – Marie Geoscience Data System. URL: http://www.marine-geo.org/tools/search/Files.php?data_set_uid=9718
- Von Damm KL (1990) Seafloor Hydrothermal Activity: Black Smoker Chemistry and Chimneys. Annu Rev Earth Pl Sc 18:173–204.

- Von Damm KL, Parker CM, Zierenberg RA, Lilley MD, Olson EJ, Clague DA, McClain JS (2005) The Escanaba Trough, Gorda Ridge hydrothermal system: Temporal stability and subseafloor complexity. *Geochim Cosmochim Acta* 69:4971-4984. doi: 10.1016/j.gca.2005.04.018.
- Wang Y, Han X, Petersen S, Jin X, Qiu Z, Zhu J (2014) Mineralogy and geochemistry of hydrothermal precipitates from Kairei hydrothermal field, Central Indian Ridge. *Mar. Geol.* 354, 69–80.
- Wang H, Li X, Chu F, Li Z, Wang J, Yu X, Bi D (2018) Mineralogy, geochemistry, and Sr-Pb isotopic geochemistry of hydrothermal massive sulfides from the 15.2°S hydrothermal field, Mid-Atlantic Ridge. *J Marine Syst* 180:220–227.
- Webber AP, Roberts S, Murton BJ, Hodgkinson MRS (2015) Geology, sulfide geochemistry and supercritical venting at the Beebe Hydrothermal Vent Field, Cayman Trough. *Geochem Geophys Geosy* 16:2661–2678.
- Wu Z, Sun X, Xu H, Konishi H, Wang Y, Wang C, Dai Y, Deng X, Yu M (2016). Occurrences and distribution of “invisible” precious metals in sulfide deposits from the Edmond hydrothermal field, Central Indian Ridge. *Ore Geol Rev* 79:105–132.
- Ye J, Shi X, Yang Y, Le, N, Liu J, Su W (2012) The occurrence of gold in hydrothermal sulfide at Southwest Indian Ridge 49.6°E. *Acta Oceanol Sin* 31:72–82.
- Yeats CJ, Parr JM, Binns RA, Gemmel JB, Scott SD (2014) The SuSu Knolls hydrothermal field, Eastern Manus Basin, Papua New Guinea: An active submarine high-sulfidation copper-gold system. *Econ Geol* 109:2207–2226.
- Zeng Z, Chen D, Yin X, Wang X-Y, Zhang G-L, Wang X-M (2010) Elemental and isotopic compositions of the hydrothermal sulfide on the East Pacific Rise near 13°N. *Sci China Earth Sci* 53:253–266.

Zeng Z, Yu S, Yin X, Wang X-Y, Zhang G-L, Wang X-M, Chen D-G (2009) Element enrichment and U-series isotopic characteristics of the hydrothermal sulfides at Jade site in the Okinawa Trough. *Sci China Ser D-Earth Sci* 52:913–924.